New vector boson near the Z-pole and the puzzle in precision electroweak data

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We show that a Z' with suppressed couplings to the electron compared to the Z-boson, with couplings to the b-quark, and with a mass close to the mass of the Z-boson, provides an excellent fit to forward-backward asymmetry of the b-quark and R_b measured on the Z-pole and ± 2 GeV off the Z-pole, and to A_e obtained from the measurement of left-right asymmetry for hadronic final states. It also leads to a significant improvement in the total hadronic cross section on the Z-pole and R_b measured at energies above the Z-pole. In addition, with a proper mass, it can explain the excess of $Zb\bar{b}$ events at LEP in the 90–105 GeV region of the $b\bar{b}$ invariant mass.

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I. INTRODUCTION

Precision electroweak measurements at LEP, SLC and the Tevatron confirmed numerous predictions of the standard model (SM) with a large degree of accuracy [1–3]. Occasionally, deviations from SM expectations appeared, and are still appearing at the Tevatron, however most of them disappeared with more data. Among those that remain, perhaps the longest lasting one, is a discrepancy in the determination of the weak mixing angle from the LEP measurement of the forward-backward asymmetry of the b-quark, $A_{\rm FB}^b$, and from the SLD measurement of left-right asymmetry for hadronic final states, A_e(LR-had.).

These two measurements, showing the largest deviations from SM predictions among Z-pole observables, create a very puzzling situation [3,4]. Varying SM input parameters, especially the Higgs boson mass, one can fit the experimental value for one of them only at the expense of increasing the discrepancy in the other one. While $A_{\rm FB}^b$ prefers a heavy Higgs boson, $m_h \simeq 400$ GeV, A_e(LR-had.) prefers $m_h \simeq 40$ GeV. Since other observables also prefer a lighter Higgs, the focus has been on possible new physics effects that modify $A_{\rm FB}^b$. However, if the pull for a large Higgs mass from $A_{\rm FB}^b$ is removed, the global fit preference is in tension with the LEP exclusion limit, $m_h > 114$ GeV [5]. In addition, it seems difficult to completely explain these deviations by a new physics and thus it is widely believed that at least part of the problem is experimental.

We show that a Z' with a mass close to the mass of the Z-boson provides an excellent fit to measurements of $A_{\rm FB}^b$ on and near the Z-pole, and simultaneously to A_e(LR-had.). It also improves on the total hadronic cross section on the Z-pole and R_b measured at energies above the Z-pole. In addition, with a proper mass, it can explain the 2.3σ excess of $Zb\bar{b}$ events at LEP in the 90–105 GeV region of the $b\bar{b}$ invariant mass.

II. Z' MODEL

We consider a new vector boson, Z', associated with a new gauge symmetry $U(1)'$, with couplings to the electron and the b-quark:

$$\mathcal{L} \supset Z'_\mu \bar{e}\gamma^\mu(g_L^{\prime e}P_L + g_R^{\prime e}P_R)e + Z'_\mu \bar{b}\gamma^\mu(g_L^{\prime b}P_L + g_R^{\prime b}P_R)b.$$

Without any assumptions about the origin of the Z', all four couplings and the mass of the Z' are treated as free parameters [6]. Couplings to other SM fermions and the mixing with the Z boson are assumed to be negligible and are set to zero for simplicity. Problems associated with a general set of couplings can be cured: chiral gauge anomalies can be canceled by introducing additional fermions, and Yukawa couplings can be generated by a Froggatt-Nielsen type mechanism; or they can be avoided by charging the SM fields under the $U(1)'$ through effective higher-dimension operators [7].

III. Z' NEAR THE Z-POLE

To demonstrate the basic feature of the effect a Z' can have on precision electroweak data, let us write the formulas for relevant observables in terms of "helicity cross section factors." The differential cross section for $e_L\bar{e}_L \to f_L\bar{f}_L$ due to an s-channel exchange of a vector boson is given by $d\sigma_{LL}/d\cos\theta \propto (g_L^e g_L^f)^2(1+\cos\theta)^2$, where $g_{L,R}^f$ are couplings of the corresponding fermion to the vector boson, and similarly for other helicity combinations: LR, RL, and RR (with a minus sign in front of $\cos\theta$ in the case of LR and RL) [1]. Depending on observable, differential cross sections are integrated over various ranges of the scattering angle θ, thus it is useful to define the helicity cross section factors as factors in differential cross sections that do not depend on the scattering angle, $\hat{\sigma}_{\rm LL} \propto (g_L^e g_L^f)^2$, and similarly for other helicity combinations. In terms of these helicity cross section factors, the forward-backward asymmetry of the b-quark can be written as

$$A_{\rm FB}^b = \frac{3}{4}\frac{\hat\sigma_{\rm LL}^b - \hat\sigma_{\rm LR}^b - \hat\sigma_{\rm RL}^b + \hat\sigma_{\rm RR}^b}{\hat\sigma_{\rm LL}^b + \hat\sigma_{\rm LR}^b + \hat\sigma_{\rm RL}^b + \hat\sigma_{\rm RR}^b} \stackrel{Z\,\rm only}{\longrightarrow} \frac{3}{4}A_e A_b, \qquad (1)$$

where the first part directly follows from integration of differential cross sections over forward and backward hemispheres. In the case of the Z-boson exchange only the $A_{\rm FB}^b$ reduces to the product of the electron and b-quark asymmetry parameters, defined as $A_f = (g_L^{f2} - g_R^{f2})/(g_L^{f2} + g_R^{f2})$ for a fermion f. Similarly, the left-right asymmetry for the b-quark final state can be written as

$$A_{\rm LR}^b = \frac{\hat\sigma_{\rm LL}^b + \hat\sigma_{\rm LR}^b - \hat\sigma_{\rm RL}^b - \hat\sigma_{\rm RR}^b}{\hat\sigma_{\rm LL}^b + \hat\sigma_{\rm LR}^b + \hat\sigma_{\rm RL}^b + \hat\sigma_{\rm RR}^b} \stackrel{Z\,\rm only}{\longrightarrow} A_e, \qquad (2)$$

and in the case of the Z-boson contribution only, it reduces to A_e, for any final state. The left-right forward-backward asymmetry of the b-quark can be written as

$$A_{\rm LRFB}^b = \frac{3}{4}\frac{\hat\sigma_{\rm LL}^b - \hat\sigma_{\rm LR}^b + \hat\sigma_{\rm RL}^b - \hat\sigma_{\rm RR}^b}{\hat\sigma_{\rm LL}^b + \hat\sigma_{\rm LR}^b + \hat\sigma_{\rm RL}^b + \hat\sigma_{\rm RR}^b} \stackrel{Z\,\rm only}{\longrightarrow} \frac{3}{4}A_b, \qquad (3)$$

and it is given by A_b in the case of the Z-boson contribution only. Finally, the ratio of the b-quark and hadronic cross sections can be written as

$$R_b = \frac{\hat\sigma_{\rm LL}^b + \hat\sigma_{\rm LR}^b + \hat\sigma_{\rm RL}^b + \hat\sigma_{\rm RR}^b}{\sum_f(\hat\sigma_{\rm LL}^f + \hat\sigma_{\rm LR}^f + \hat\sigma_{\rm RL}^f + \hat\sigma_{\rm RR}^f)}. \qquad (4)$$

Previous explanations of the deviation in $A_{\rm FB}^b$ focused on modifying g_R^b. Achieving this and simultaneously not upsetting quite precise agreement in R_b turned out to be very challenging for a new physics that enters through loop corrections [8]. This motivated tree-level modification of the g_R^b either through mixing of b-quark with extra fermions [9] or through Z-Z' mixing [10]. However the $A_{\rm FB}^b$ is only a part of the puzzle and, as is clear from Eq. (2), any new physics that reduces to modification of bottom quark couplings cannot affect the A_e(LR-had.).

We suggest modifying the $b\bar b$ production cross section directly, $e^+e^- \to Z'^* \to b\bar b$, rather than modifying the Z-couplings. This idea comes from a simple observation that increasing $\hat\sigma_{\rm LR}^b$ so that R_b increases by about 0.4% (which still produces a better fit than the standard model) decreases $A_{\rm FB}^b$, see Eq. (1), by $\sim$4% which is exactly what is needed to fit the experimental value. This 10 times larger effect is a result of an approximate, $\sim$90%, cancellation between $\hat\sigma_{\rm LL}^b$ and $\hat\sigma_{\rm RL}^b$ in the SM due to comparable g_L^e and g_R^e couplings. For the same reason, A_e(LR-had.) increases by $\sim 4\%/5 = 0.8\%$, see Eq. (2) (the factor of 5 comes from $b\bar b$ representing $\sim$20% of hadronic final states), which brings it to $\sim 1\sigma$ from the experimental value.

To generate a sizable contribution to $A_{\rm FB}^b$ on the Z-pole and not significantly affect predictions for $A_{\rm FB}^b$ and R_b above the Z-pole (that roughly agree with measurements), the increase in $\hat\sigma_{\rm LR}^b$ must be due to s-channel exchange of a new vector particle with mass close to the mass of the Z-boson. A scalar particle near the Z-pole can modify $A_{\rm FB}^b$ only comparably to its modification of R_b. This was considered in Ref. [11], motivated by previous discrepancies in Z-pole observables. Similarly Z' was used to explain previous discrepancies, see, e.g., a heavy Z' [12] or almost degenerate Z and Z' [13] scenarios. A heavy particle, or a particle contributing in t-channel, can modify Z-pole observables only negligibly if it should not dramatically alter predictions above the Z-pole. Thus a Z' near the Z-pole with small couplings to the electron (in order to satisfy limits from searches for Z') and sizable couplings to the bottom quark is the only candidate.

IV. NUMERICAL ANALYSIS

We construct a χ^2 function of relevant quantities related to the bottom quark and electron measured at and near the Z-pole, which are summarized in Table I. Their precise definition can be found in the EWWG review [1] from which we also take the corresponding experimental values. Instead of the pole forward-backward asymmetry of the b-quark, $A_{\rm FB}^{0,b}$, we include three measurements of the asymmetry, at the peak and ± 2 GeV from the peak. These are more relevant because the presence of a Z' near the Z-pole changes the energy dependence of the asymmetry. In addition, about 25% of the deviation in the pole asymmetry comes from the measurement at $+2$ GeV from the peak. Corresponding LEP averages for R_b at ± 2 GeV from the peak do not exist. These are available only from DELPHI [14] and although they are included in the Z-pole LEP average, R_b^0, we include them in addition in order to constrain the energy dependence. We further include pole values of the total hadronic cross section, $\sigma_{\rm had}^0$, the ratio of the hadronic and electron decay widths, R_e^0, forward-backward asymmetry of the electron, $A_{\rm FB}^{0,e}$, measured at LEP; and SLD values of asymmetry parameters of the b-quark, A_b, obtained from the measurement of left-right forward-backward asymmetry, and the electron, obtained from the measurement of left-right asymmetry for hadronic final states, A_e(LR-had.), and leptonic final states, A_e(LR-lept.).

We calculate theoretical predictions using ZFITTER 6.43 [15,16] and ZEFIT 6.10 [17], which we modified for a Z' with free couplings to the b-quark and the electron. In our fit we use the SM input parameters summarized in Table 8.1 of the EWWG review [1], namely: $m_Z = 91.1875$ GeV, $\Delta\alpha^{(5)}(m_Z^2) = 0.02758$, $\alpha_S(m_Z^2) = 0.118$; however, we update the top quark mass to the Tevatron average, $m_t = 173.3$ GeV [18], and fix the Higgs mass to $m_H = 117$ GeV. We minimize the χ^2 function of 5 parameters, $m_{Z'}$, $g_L'^e$, $g_R'^e$, $g_L'^b$, and $g_R'^b$, with MINUIT [19]. In

TABLE I. The best fit to relevant precision electroweak observables in the SM with a Z'. The best fit is achieved for: $m_{Z'} = 92.2$ GeV, $g_L'^e = 0.0059$, $g_R'^e = 0.0073$, $g_L'^b = 0.040$, and $g_R'^b = -0.54$; ($\Gamma_{Z'} = 1.1$ GeV). The standard model input parameters are fixed to $m_t = 173.3$ GeV, $m_h = 117$ GeV, and other parameters as listed in Table 8.1 of the EWWG review [1]. For comparison, we also include predictions of the standard model with χ^2 contributions.

Quantity	Exp. value	SM	χ^2_{SM}	Z'	$\chi^2_{Z'}$
σ^0_{had} [nb]	41.541(37)	41.481	**2.6**	41.529	**0.1**
$R_b(-2)$	0.2142(27)	0.2150	0.1	0.2156	0.3
R_b^0	0.21629(66)	0.21580	0.6	0.21670	0.4
$R_b(+2)$	0.2177(24)	0.2155	0.8	0.2177	0.0
$A^b_{FB}(-2)$	0.0560(66)	0.0638	**1.4**	0.0577	**0.1**
$A^b_{FB}(pk)$	0.0982(17)	0.1014	**3.5**	0.0979	**0.0**
$A^b_{FB}(+2)$	0.1125(55)	0.1255	**5.6**	0.1136	**0.0**
A_b	0.923(20)	0.9346	0.3	0.9237	0.0
R_e^0	20.804(50)	20.737	1.8	20.765	0.6
$A^{0,e}_{FB}$	0.0145(25)	0.0165	0.7	0.0174	1.4
A_e(LR-had.)	0.15138(216)	0.14739	**3.4**	0.15014	**0.3**
A_e(LR-lept.)	0.1544(60)	0.1473	1.4	0.1473	1.4
total χ^2			22.1		4.6

principle, the width, $\Gamma_{Z'}$, could be treated as a free parameter because Z' can have additional couplings that do not affect precision electroweak data. For simplicity, we do not consider this possibility.

V. THE BEST FIT SOLUTION

The best fit to precision data included in the χ^2 is summarized in Table I and parameters for which the best fit is obtained are given in the caption. Clearly, addition of Z' provides an excellent fit to selected precision electroweak data with $\chi^2 = 4.6$ for 12 observables with 5 additional parameters compared to the standard model that has $\chi^2 = 22$. The most significant improvement comes from the three measurements of A^b_{FB} which can be fit basically at central values in the Z' model, without spoiling the agreement in R_b. The energy dependence of both quantities near the Z-pole for both the SM and Z' model together with data points is plotted in Fig. 1. The A_e(LR-had.) and σ^0_{had} are also fit close to their central values.

Besides quantities included in the χ^2 and given in Table I, we check all other electroweak data on and near the Z-pole, and above and below the Z-pole. While b-quark quantities were measured at three energies near the Z-pole, the total hadronic cross section was measured also at ± 1, 3 GeV (from data collected only during 1990–1991). The measurement at $+1$ GeV roughly coincides with the Z'-peak where the deviation from the SM would be the largest. The experimental error in σ_{had} at $+1$ GeV from the peak is $\sim 1\%$ for each LEP experiment and thus the Z'-peak contributes only a fraction of the error bar.

At energies above the Z-pole, the A^b_{FB} in the Z' model basically coincides with the SM prediction while R_b fits data better than the SM, see Fig. 1, with $\chi^2 = 4.8$ for 10 data points compared to the SM which has $\chi^2 = 7.2$ (the average discrepancy with respect to the SM prediction for R_b is -2.1σ) [2]. At energies below the Z-pole the Z' leads only to negligible differences from the SM predictions compared to sensitivities of current experiments.

The quantities related to other charged leptons and quarks are not directly affected by Z' and the predictions are essentially identical to predictions of the SM [3]. For example, the LEP 1 average of leptonic asymmetry assuming lepton universality, $A_l = 0.1481 \pm 0.0027$, agrees very well with the SM prediction and would be only negligibly altered by the Z' with couplings corresponding to the best fit (the prediction is the same as for A_e(LR-lept.) given in Table I).

VI. OTHER FITS

The full exploration of the Z' parameter space is beyond the scope of this article. However, it is instructive to make few comments. The χ^2 is a very shallow function of the Z' parameters, except the Z' mass. Varying couplings by 10% leads to a comparable fit. Actually, almost all the improvement in the χ^2 comes from the $g_L'^e$ and $g_R'^b$ couplings, because these are needed to modify $\hat{\sigma}^b_{LR}$ as discussed above. With only these two couplings the best fit is achieved for: $m_{Z'} = 92.1$ GeV, $g_L'^e = 0.0048$, and $g_R'^b = -0.47$ with $\chi^2 = 6.4$ (only slightly worse than the best fit with all the couplings). In addition, values of couplings separately are not crucial, as far as $g_L'^e$ is small, not upsetting electron observables. Thus this striking improvement in the χ^2 for the Z-pole and near the Z-pole observables is achieved with only two relevant parameters: $m_{Z'}$ and the product of couplings, $(g_L'^e g_R'^b)$.

Increasing the Z' mass the fit gets worse, mostly driven by measurements of R_b near the Z-pole (corresponding values of the total hadronic cross section near the Z-pole, which are not included in the χ^2, are also affected). Fixing the Z' mass to 95 GeV, the best fit is achieved for somewhat

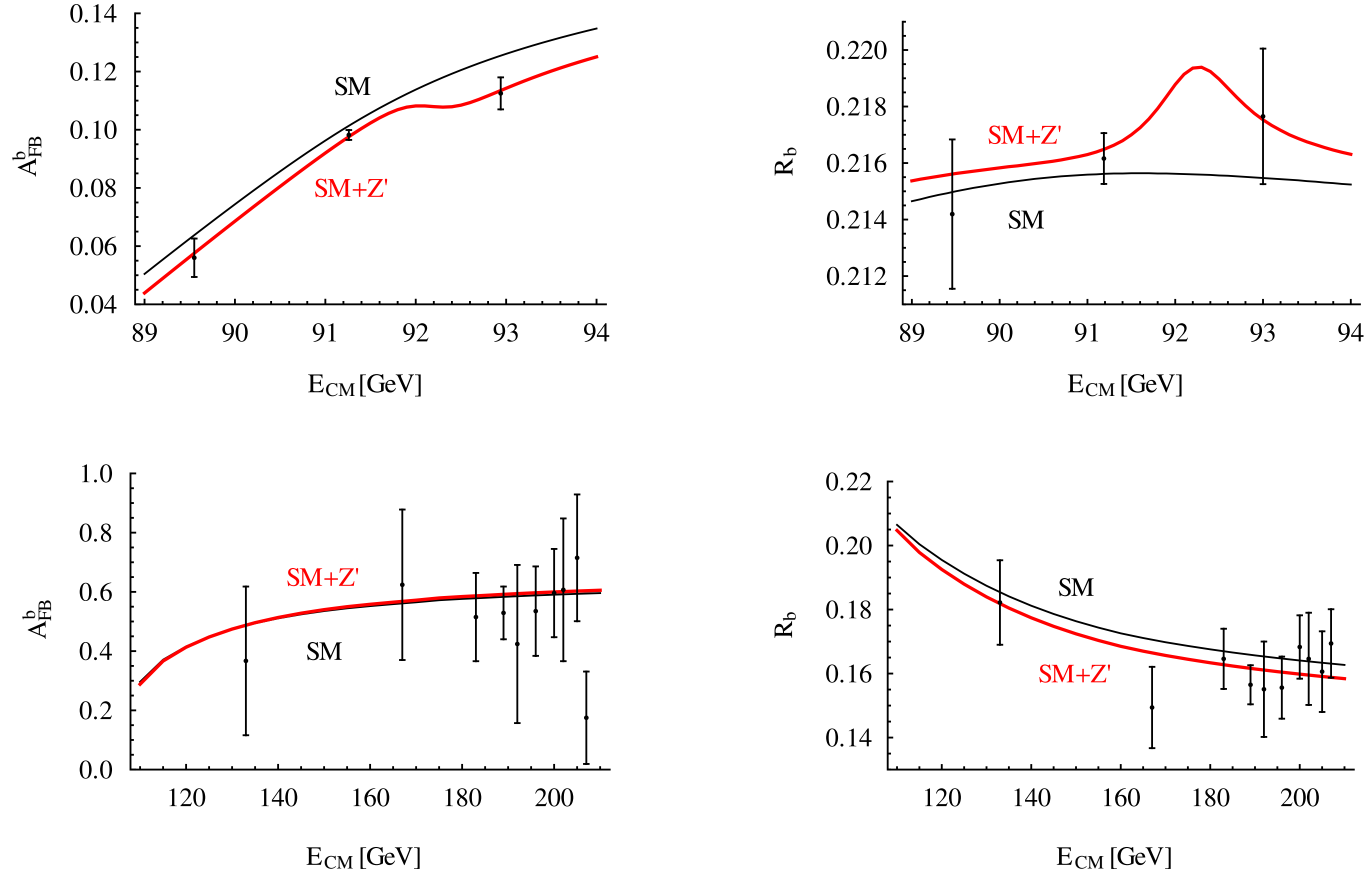

FIG. 1 (color online). Experimental values of $A^b_{\rm FB}$ and R_b and predictions of the SM (thin lines) and the Z' model (thick lines) for input parameters specified in the caption of Table I as functions of center of mass energy near and above the Z-pole.

larger couplings to electrons: $g_L^{\prime e} = 0.027$, $g_R^{\prime e} = 0.013$, $g_L^{\prime b} = 0.08$, and $g_R^{\prime b} = -0.49$ with $\chi^2 = 9.3$, which is still a significant improvement from the SM. Increasing the Z' mass above $\sim$110 GeV improves the fit to precision electroweak data only marginally.

VII. OTHER CONSTRAINTS

At LEP Z' could be produced together with the Z-boson, $e^+e^- \to ZZ'$, or pair produced. If other couplings besides $g^{e,b}_{L,R}$ are absent, the Z' would decay to $b\bar{b}$ with branching ratio close to 100% and thus it would result in a small excess in $Zb\bar{b}$ and a negligible excess in $b\bar{b}b\bar{b}$ data that were closely scrutinized in searches for Higgs bosons. The search for the SM Higgs boson in $Zb\bar{b}$ final state shows a 2.3σ excess of events for the $b\bar{b}$ invariant mass in the range 90–105 GeV [5]. It is compatible with $\sim$10% of the SM Higgs production cross section for $m_h = 100$ GeV, and thus it can be explained either by a Higgs boson with reduced coupling to the Z-boson [20–22] or a SM-like Higgs boson with reduced branching fraction to $b\bar{b}$ [23–25].

The Z' with properties studied in this paper can provide another explanation. The best fit presented in Table I can explain only a fraction of the excess (extra $\sim$5 fb of $Zb\bar{b}$ cross section). However, as already mentioned, increasing $g^{\prime e}_{L,R}$ and decreasing $g^{\prime b}_{L,R}$ so that their products are the same leads to small differences in the χ^2. Thus $\sigma(e^+e^- \to ZZ')$ which depends only on $g^{\prime e}_{L,R}$ can be adjusted. For example, the best fit with fixed $m_{Z'} = 95$ GeV (see above) contributes extra 36 fb of $Zb\bar{b}$ cross section, which is about 10% of the SM Higgs production cross section, perfectly matching the excess.

The same search also showed a deficit of $Zb\bar{b}$ events for the $b\bar{b}$ invariant mass below the Z-mass. It would be interesting to see whether this deficit can be a result of the negative interference of Z' with γ and Z in $e^+e^- \to Z(\gamma^*, Z^*, Z'^*) \to Zb\bar{b}$. This requires a careful study.

At the Tevatron this Z' could be produced only in association with b-quarks. The $Z'b$ cross section can be easily estimated from studies of the Zb production which is a background for Higgs searches [26]. For the three fits discussed above we find $\sigma(p\bar{p} \to Z'b) \simeq$ 20–30 pb. Both CDF and D0 searched for the Higgs boson produced in association with b-quarks [27,28], and set limits $\sigma(p\bar{p} \to Hb) \times B(H \to b\bar{b}) <$ 30–50 pb for $m_H \simeq$ 90–100 GeV [27]. This is not very far from the prediction and thus updated analyses with larger data sets might see an excess or start constraining the size of $g_R^{\prime b}$. At the LHC the $Z'b$ cross section is 2 orders of magnitude larger [26] and it is just a question of accumulating enough luminosity to see the signal of Z'. Note however, that with possible couplings of Z' to other quarks (or particles beyond the SM) the $B(Z' \to b\bar{b})$ can be highly reduced which could make the search for Z' difficult.

VIII. CONCLUSIONS AND OUTLOOK

The Z' near the Z-pole with couplings to the electron and the b-quark can resolve the puzzle in precision electroweak data by explaining the two largest deviations from SM predictions among Z-pole observables: $A_{\rm FB}^b$ and A_e(LR-had.). It nicely fits the energy dependence of $A_{\rm FB}^b$ near the Z-pole and improves on $\sigma_{\rm had}^0$ on the Z-pole and R_b measured at energies above the Z-pole. Certainly it is possible that all these deviations from the SM are just statistical fluctuations and systematic errors, or a combination of these with effects of much more complicated new physics. However it is intriguing that these deviations, together with the 2.3σ excess of $Zb\bar{b}$ events at LEP that can be fully explained by Z', might as well be hints of a new force of nature.

Besides the Tevatron and the LHC, where this Z' might be seen in b-quark rich events, the optimal experiment to confirm or rule out this possibility would be the future linear collider, especially the GigaZ option, which would allow more accurate exploration of the Z-peak.

Considering other flavor conserving couplings, or small flavor violating couplings, expands the range of observables to which this Z' could contribute. It would be interesting to see if it can simultaneously explain some other deviations from SM predictions.

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